FIBER OPTIC COIL - FABRICATION AND CHARACTERIZATION

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

Page

ABSTRACT

Fiber Optic Coil - Fabrication and Characterization

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The goal is to develop a device which periodically couples a pump signal to a signal propagating within a fiber such that the highest amount of optical gain is observed. This idea is based off the proposition that using some form of pump signal will positively contribute to the signal strength within the core of an active fiber configured in a circular coiled arrangement. Initial testing will include measuring the decibel losses of fiber coils as a function of the number of turns, and then using this gathered data to determine the optimal range of wavelengths, and thus the corresponding modes, for propagation to accept pumping. However, we are still in the process of determining what fiber materials and geometries are most appropriate to use for the above described application. If the idea of a fiber embedded cylinder proves to be sufficient model for boosting the signal within the fiber core, its application lies in a variety of fields and devices within electrical engineering, potentially as a resonator, but more likely as an amplifier utilizing a separate pump source to provide external power to an active fiber optic line. Given the result of the successful development of such embedded cylinders, further studies will likely include systems of such devices and an examination into which other fields these cylinders and corresponding systems can be applied.

CHAPTER I

INTRODUCTION

Overview

Optical fibers are a type of waveguide which have experienced a variety of real world applications in telecommunications and signal processing since their invention in the early 1970's. An optical fiber is designed with a greater refractive index within its core than the index of the cladding. In accordance with Snell's law, a propagating light wave will repeatedly bounce between the core-cladding interface for a given incidence angle and remain inside the core with little attenuation. This phenomena is known as Total Internal Reflection, and this is generally how light propagates within fiber lines for telecommunication applications. However, if the incidence angle becomes too extreme due to changing spatial characteristics, like bending the fiber, then some light will escape and loss will be observed, resulting in a phenomenon known as Bend Loss. See Figure 1A below for visual representation of Total Internal Reflection (depicted above) and Bend Loss (depicted below).

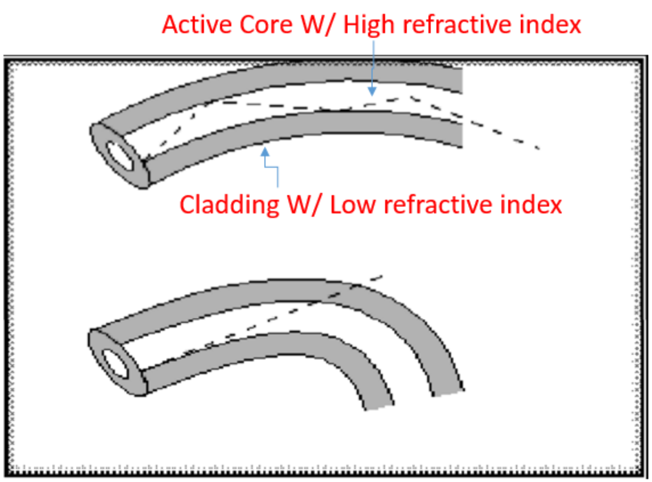

Figure 1A: Isotropic pumping example.

As with all forms of communication, amplification of the signal is essential for functionality. A fiber laser achieves gain by taking advantage of the relationship between the spectral absorption and emission characteristics of its ‘active’, rare-earth doped core. Under most circumstances, scientists and engineers implement this gain using an erbium-doped fiber amplifier, abbreviated as EDFA. Optical power of a specific ‘pump’ frequency, which may be monochromatic or broadband light, can be transformed by these active media to a lower ‘signal’ frequency, such that any existing signal frequency modes effectively absorb power from the pump[1]. Hence, if a doped fiber’s geometry is such that the pump signal frequency satisfies the single mode condition, or if the appropriate pump signal can excite the active core, any pump power that traverses the active core can be absorbed and re-emitted in this single dominant propagating mode; this process defined as signal coupling. In addition, the coupling process is completely isotropic. In other words, it is independent of the pump power’s direction, and because of this, the practice of counter-directional pumping (pumping against the direction of propagation) a fiber laser achieves very similar cross sectional gain to co-directional pumped (pumping in the direction of propagation) fiber lasers. Figure 1B below depicts pumping from laser diodes in a co-directional fashion on the left and in a counter-directional fashion on the right.

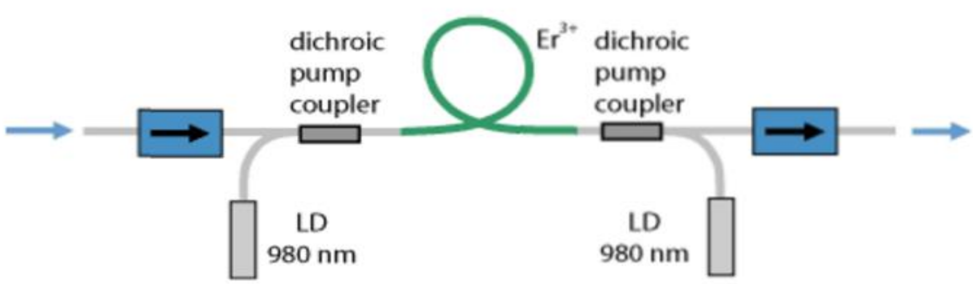

Figure 1B: Isotropic pumping example.

Again, given the isotropic nature of this energy transfer, achieving desired gain from the pump signal simply entails its interaction with the propagating signal within the core of the fiber. Direct pump will be focused onto a coupling structure on a curved side of the cylinder, where it will propagate by total internal reflection around the cylinder multiple times with some light inevitably escaping due to bend loss. Since the fiber is coiled and embedded within the same cylindrical structure, pump rays will have the chance to periodically couple to the core. This setup allows the signal frequency's wave-guiding core to remain physically isolated - there is no fusion coupling of a pump and signal fiber. If the geometry of the structure is properly designed and accounted for, periodic coupling may be achieved and serve to provide more interactions, and thus more gain, with the information carrying signal than a general straight fiber. A device that can readily accept a pump source would prove to be hugely beneficial here since coupling for the straight fiber is usually implement by pumping directly into the end face of the multi-mode core, which is no larger than 20 microns in diameter for even the largest multi-mode fibers. Lastly, the condensed size of the coil itself has its own benefits over the straight, uncoiled fiber amplifier topology due to the lesser amount of space that it occupies.

General objectives

Primarily, we desire to produce a pumped structure, in this case a fiber coil, capable of greater signal gain and pump power acceptability than a straight, individual fiber. Even though more loss is associated with the coil arrangement due to bend loss (light rays escaping due to their angle of incidence upon the core-clad interface exceeding the critical angle), there exists potential for more gain in the pumped structure than the straight fiber model. Initially testing will predominantly be spent gathering data related to the optical measurements, particularly measuring splice loss between the device under test and pigtails in addition to relative optical loss for the different number of windings. Next, based on the gathered optical measurements, we will determine the optimal parameters, particularly the total winds of optical fiber, for the fiber coil and then measure the associated signal gain for both the coupling with pump light penetrating into the side of the coil and no pump light cases. Once we have established the number of windings, other parameter consideration will be given for practicality of fabrication, cost effectiveness, and relative durability of the final structure.

Potential applications

Embedded fiber cylinders, are a novel idea with a tremendous amount of potential application within larger systems. They differ from fiber coils, or fiber resonators, since these arrangements are generally wrapped around a spindle, but are not physically embedded within another structure. This embedded design is attractive because of its potential to give active core optical fiber extreme ease at accepting any form of pump power.

CHAPTER II

METHODS

The gathering of optical measurements and fabrication process solely took place in the engineering laboratories provided by the university. Necessary materials for collecting data for optical loss included multimode optical fibers and pigtails, splicing equipment, pigtail fibers, monochromatic and broadband sources to produce a signal to transmit through the fiber, and a detecting device to measure optical loss or gain. Processes based off of previous fabrication methods, developed here at Texas A&M, are already in place to produce fiber-embedded cylinders with sub-millimeter wall thickness [2].

Winding process

The initial configuration process utilizes an automated coiling system to wind the optical fiber from a feed line onto an acrylic cylinder at a constant rate, thus producing a coil structure with approximately 50 winds. An Arduino micro-controller is used in conjunction with a simple electronic push-button pad to control the step motors responsible for winding and stabilizing the fiber. A series of routines were uploaded onto the micro-controller, and implemented by the external push-pad which dictated simple instructions such as number of windings to be performed, motor speed, and rotational direction. In addition, this automated coiling system played an essential role in this to this pre-fabrication process, since it introduces an element of uniformity between each test such that each additional coil is evenly spaced, for uneven spacing would likely impact the degree and predictability of coupling, and allows for each fiber to test to have its coiling loss characterized for a single coil radius of (insert cm dimension). First, one end of the line is connected to an acrylic cylinder resting on an electric motor powered spindle. To prevent excess tension and the thus the possibility of the fiber failing under such a force, pre-windings must be completed by hand (is it performed by hand?). Once the decided number of windings are iterated, the newly coiled fiber must be taped down onto the acrylic cylinder in order to ensure that it will remain on the cylinder once the feed line is cut from the fiber spool, meanwhile allowing slack on the feed line to prevent unwanted tension. Next, the pre-windings are released such that only the decided number of windings remains on the cylinder. See Figure 2A below of automated platform used to wind coils as well as Figure 2B for the acrylic cylinder with windings.

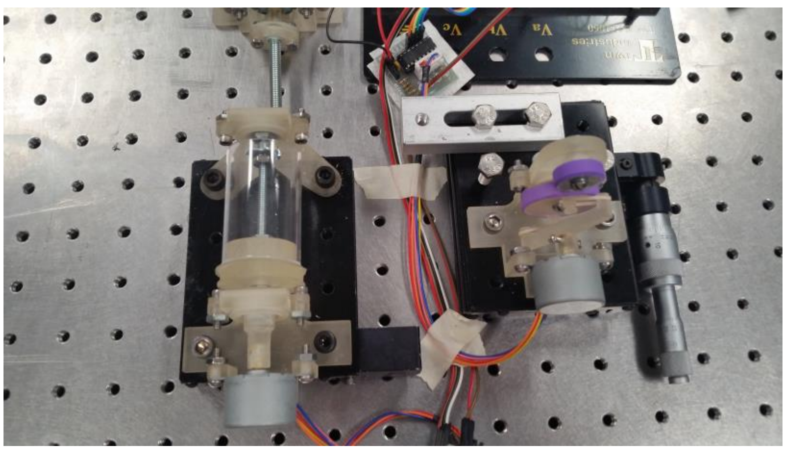

Figure 2A: Coil winding system.

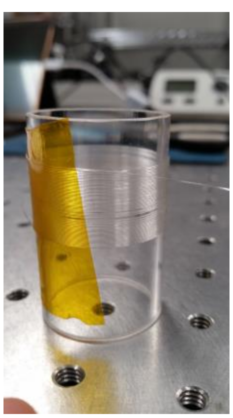

Figure 2B: Acrylic cylinder with approximately 50 windings.

Optical measurements

To begin the measurement process, connections must be established by splicing fiber ends to the pigtail and then connecting those pigtails to a detecting device and light source. First, pigtail ends had to be clipped prior to splicing, in the same fashion as the wound fiber coil. Next, both ends of the wound fiber are stripped of their coating by filling a test tube with zip-strip, a chemical with a high concentration of chlorinated solvents methylene chloride and trichloroethylene, and dipping the fiber end into the tube for at least 10 seconds to remove the entire coating. We repeated the same procedure for the pigtail ends and once completed, the ends of both pigtails were spliced together with the stripped ends of the coil fiber using an automated heat splicing machine. Furthermore, the machine has the capability of displaying estimated splice loss and core alignment, this way if there were sufficient misalignment and corresponding loss, the ends could be removed from one another in allowance for another splice to be made.

The measuring system was configured such that the multimode pigtails will connect the broadband source to the device under test and another pigtail between the device under test and the detector. Note that pigtail fibers utilize mechanical connectors to establish quick, yet not perfectly lossless connection to another pigtail fiber. To provide the signal to be measured, we established a connection between a broadband light source and the pigtail using an SMA fastener. The final pigtail, spliced to the other end of the wound coil arrangement, is connected via another SMA fastener to complete the measurement configuration. However, since the light intensity produced by the source exceeds the saturation limit of the spectrometer reading-out the loss data, an attenuator must be attached to the first pigtail before the signal reaches the coil. See Figure 2C of following page for bend loss measurement configuration.

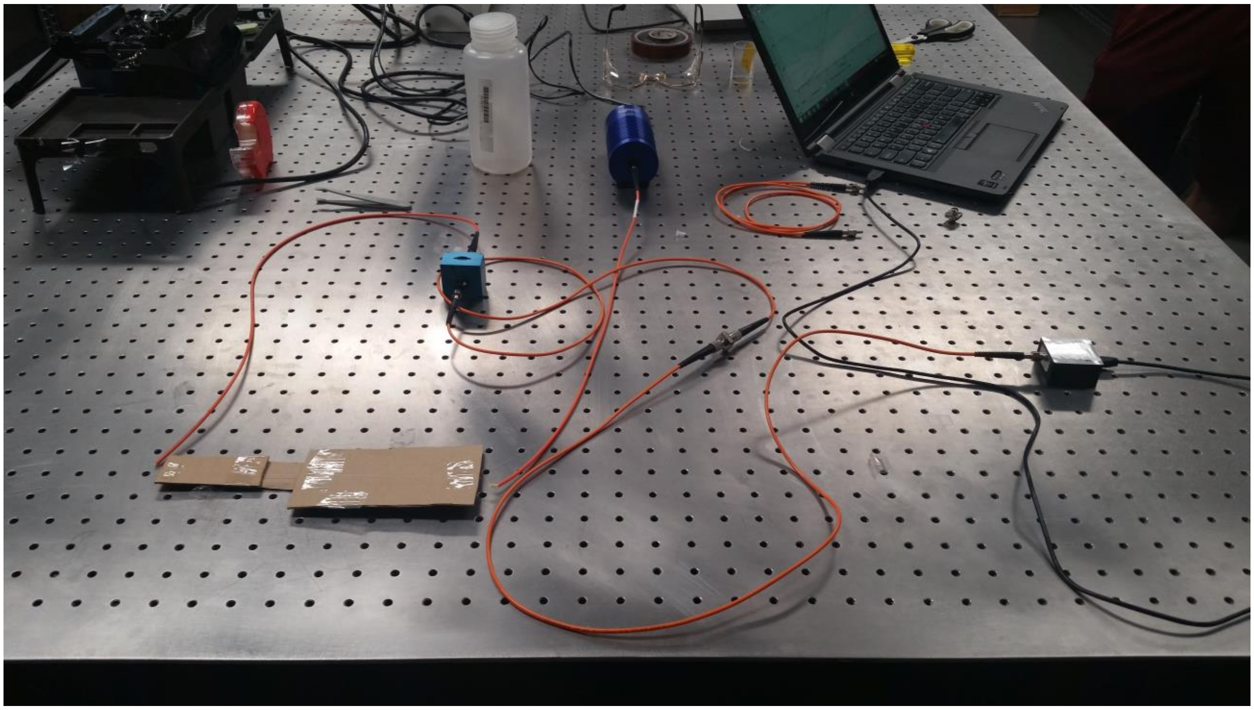

Figure 2C: Bend loss measurement configuration.

To initiate the data collection, we activated the broadband light source so that the light signal could propagate through the first pig tail, the attenuator, the fiber windings, the second pig tail, and then finally into a spectrometer whose data output was displayed on a computer via Ocean View software. Once the light intensity levels stabilized, we gathered data for wavelengths between 500nm and 1350 nm. We repeated gathering data by decreasing the windings in decrements of three by removing a small section of tape and then removing the desired number of windings. We repeated this process until there was only a straight fiber, which as mentioned earlier, serviced as our referenced.

Coil fabrication

Due to multimode fiber material constraints, we optimized the fabrication process by first making a single mode coil. We began by first coating the acrylic cylinder in paraffin wax to allow for easy separation from the stripped coil. Next, we mechanically stripped the single mode fiber and then wound it into a coil of 50 turns using the automated winding system described in the previous section. Once wound, the feed line was clipped and optically transparent epoxy was manually deposited onto the stripped coil with a syringe. To maintain a uniform coat of epoxy, the winding system was continuously spinning with an additional clean cylinder pushing against the rotating coil to rub-off the excess. Once all the epoxy was uniformly distributed onto the stripped fiber coil, medium intensity ultra-violet radiation for approximately five minutes was used to cure the liquid into a hardened shell. As seen in Figure 2D, aluminum shielding was used as a means of containment for the radiation.

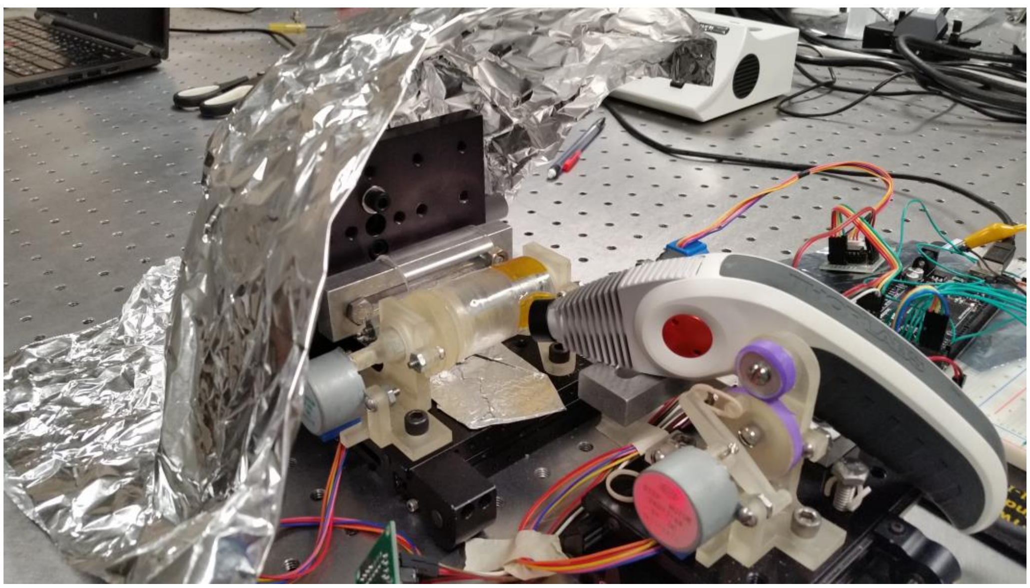

Figure 2D: Ultra-violet curing process.

For the last portion of the fabrication process, the coil was removed from the paraffin waxed covered cylinder. This was easily implemented by suspending the coil and cylinder with rubber bands so that the set of rubber bands attached to the cylinder provided tension in the opposite direction of those attached to the stripped coil. As the wax melted on the cylinder, the rubber bands pulled the coil and acrylic cylinder apart. See Figure 2E and Figure 2F below of separation apparatus and single coil prototypes.

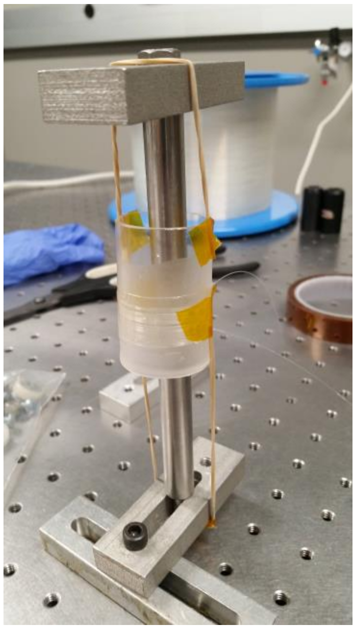

Figure 2E: Ultra-violet curing process.

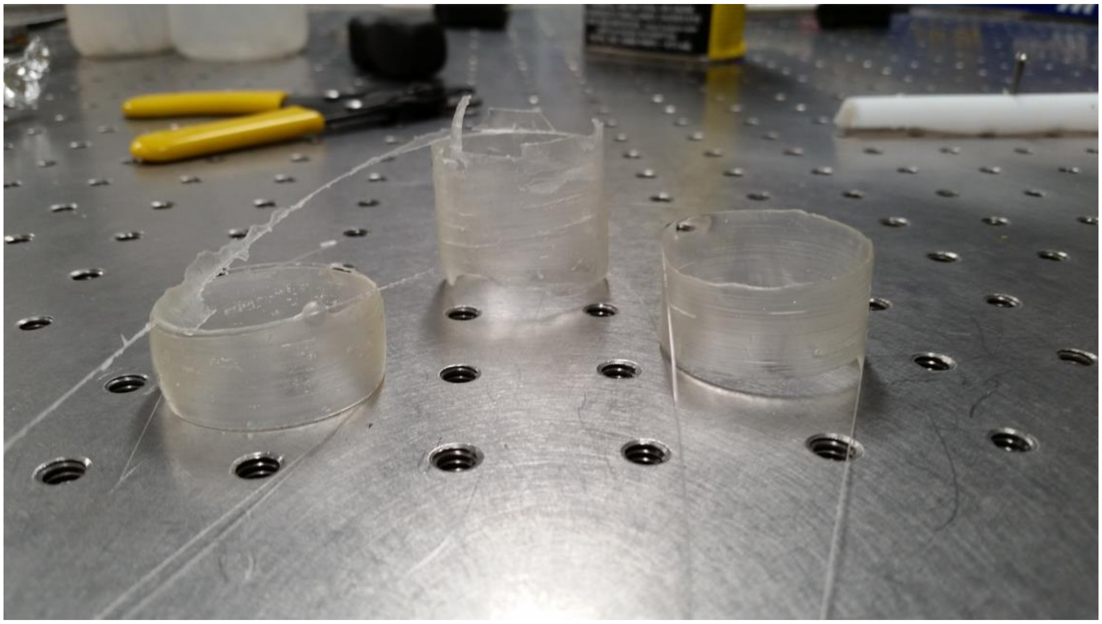

Figure 2F: Ultra-violet curing process.

The fabrication process for the multimode coil is still underway given difficulties encountered during stripping. This is not a severe drawback since the fabrication process is the same for the single mode coil, of course barring the stripping procedure. Thus far, purely mechanical stripping (only using fiber strippers) has been ruled out since no coating can be removed with breaking the fiber. Weakening the coating using zip-strip and then removing by strippers or high-grit sand paper has also been ruled out. The next attempt is directly applying the active ingredient in zip-strip, methylene chloride. This process is commonly used in optics labs, but a somewhat expensive means to strip multimode fiber.

CHAPTER III

RESULTS

Bend loss data

Below are plots of the bend loss data. Figures 3A and 3B illustrate intensities as a function of wavelength where each different color line represent coil with a known amount of turns. For figure 3A, notice the green curve exhibits the lowest intensity, on average for all wavelengths, and thus corresponds to a coil with the largest amount of turns and related bend. Similarly, the blue curve has the largest average intensity for all wavelengths and corresponds to the straight fiber, which again served as our reference.

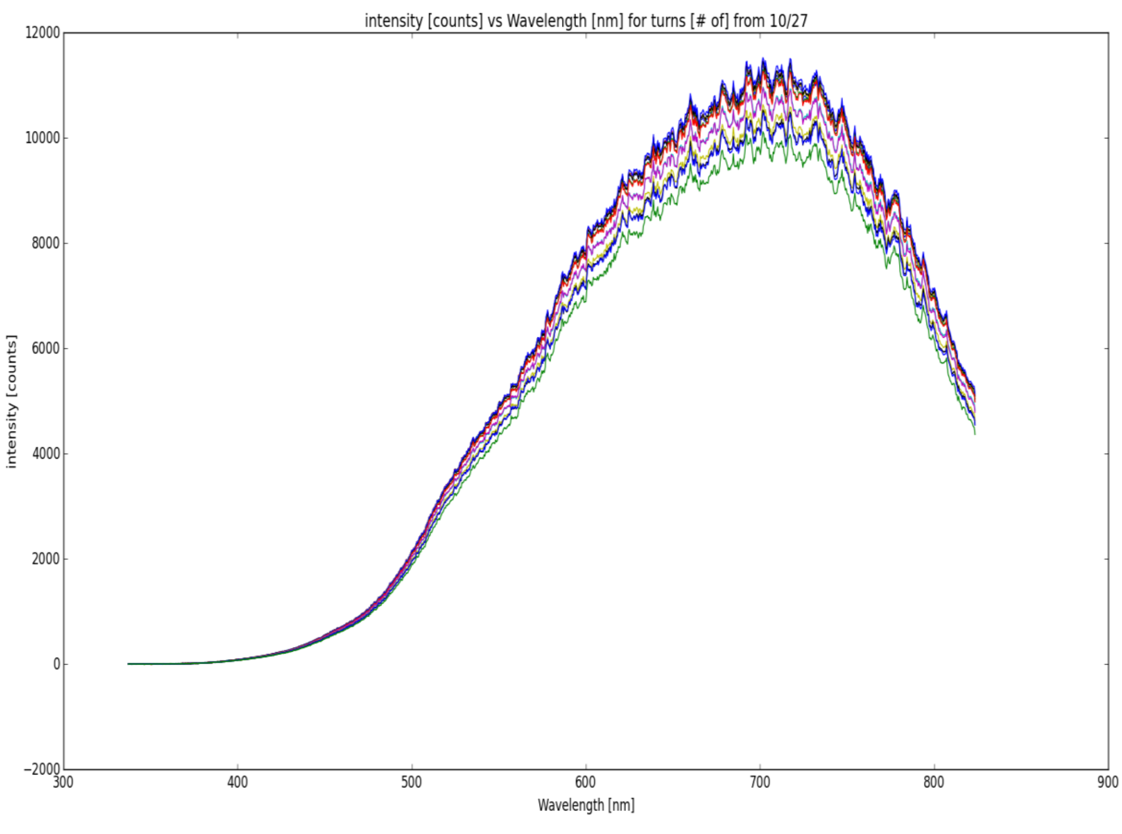

Figure 3A: Intensity as a function of wavelength using 48 windings

Figure 3B illustrates the same procedure as figure 3A, but this time using 51 windings versus 48 windings. As with the preceding figure, each different colored curve represents a coil with a known number of coils, with the curve with the largest average intensity representing our reference at zero turns and the curve with lowest intensity representing the coil with the greatest amount of turns, 51 in this case.

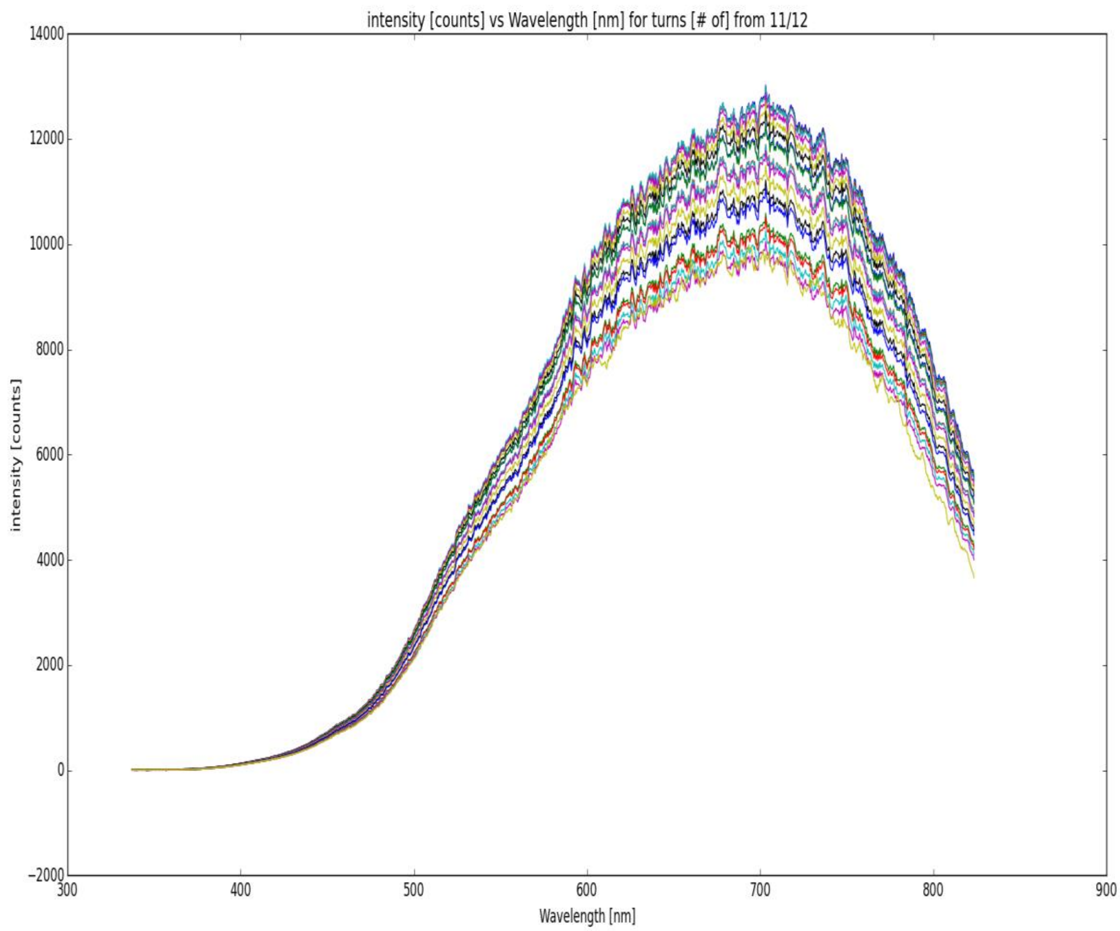

Figure 3B: Intensity as a function of wavelength using 51 windings

Figures 4A and 4B, plot decibel loss versus the number of turns with zero decibels referenced to zero turns. Each different color line corresponds to a particular range of wavelength since a broadband source was used as the input.

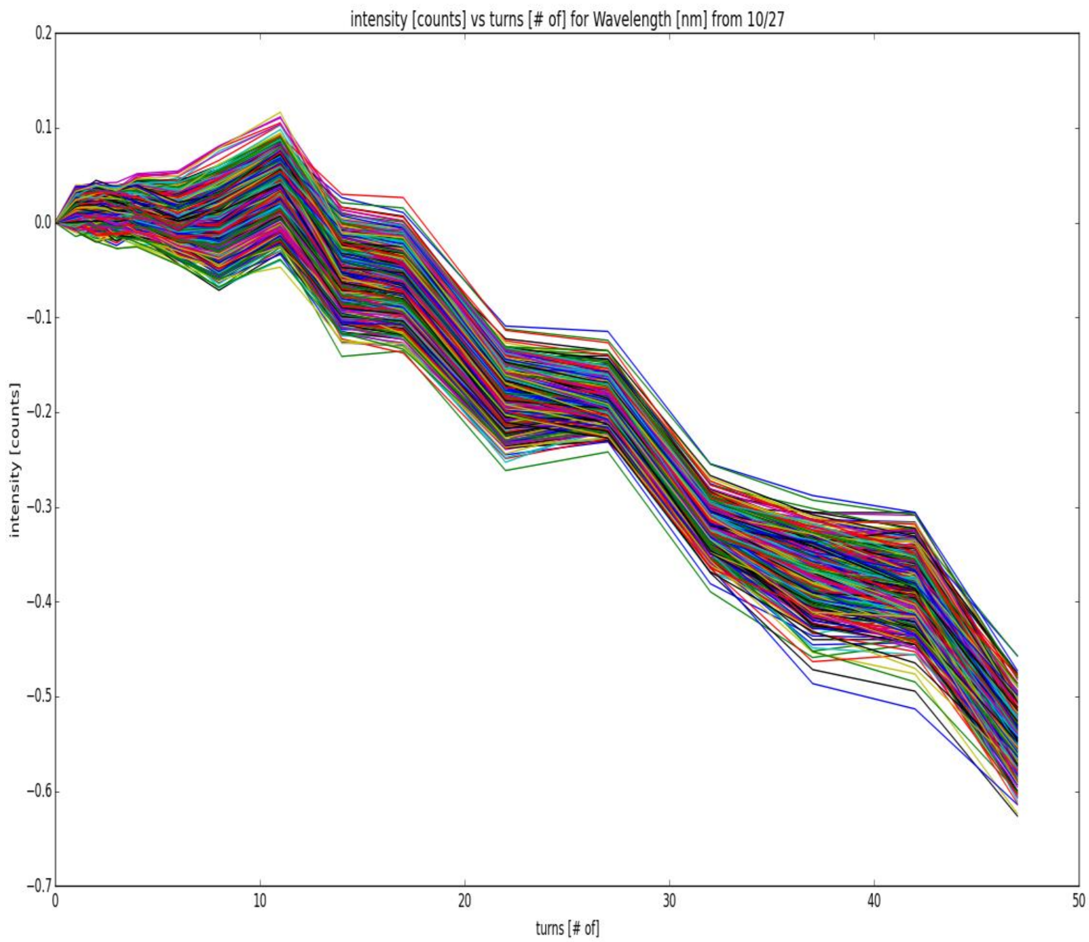

Figure 3A: Data collection using 48 windings.

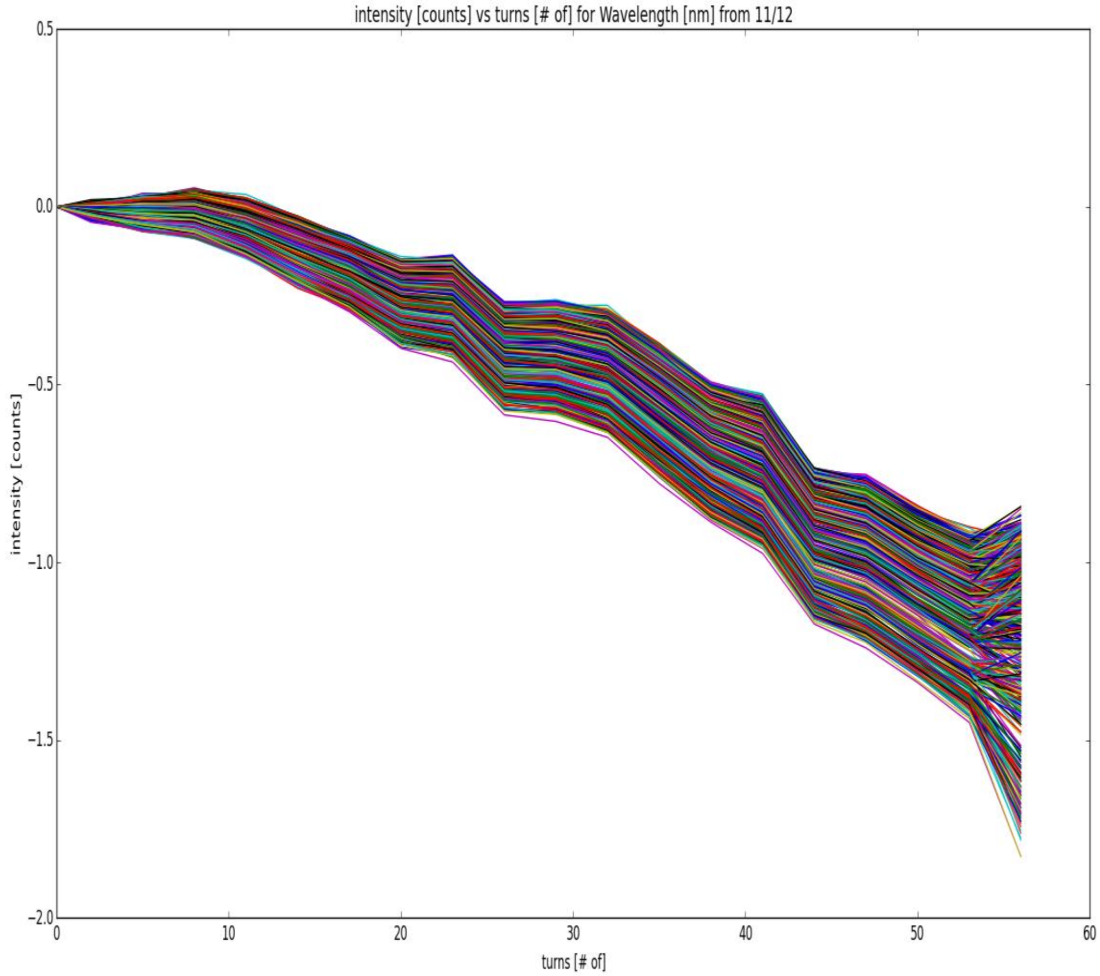

Figure 3B: Data collection using 51 windings.

Notice that both series demonstrates that more loss accumulates as more windings are added, with unity gain at zero turns. This makes sense regarding bend loss since more light escapes with the addition of more turns. The above data can be used to determine the ideal signal frequencies since according to the figure, some frequencies experience greater loss than others. The signal frequencies which experience the least amount of loss would be the best fit since only a fixed amount of pump may be absorbed based off the dimensions of the cylinder. For overall gain to be observed, the pump gain must exceed the loss due to bending. To further analyze this, note that the approximate bend losses are 0.0125 decibels per turn and 0.0294 decibels per turn for the 48 and 51 turn cases respectively.

CHAPTER IV

CONCLUSION

The project results were different than expected. Improvements were made to the automated winding system to reduce the amount of time to produce a coil as well as characterizing the bend loss of the coil geometry. However, due to drawbacks in the fabrication process, a multimode coil capable of amplifying a fiber signal was not tested before the final thesis deadline. This single drawback regarding stripping may easily be reconciled with the use of the direct application of methylene chloride. Once overcome, creating a multimode coil will be as easy as fabricating the single mode coil and pave the way for the development of a means to characterize the coupling attributes of the coil.

With the combination of bend loss and future coupling data, we will be able to determine whether the fiber coil proves to be a viable pumping scheme. If this is the case, this device concept could revolutionize the telecommunications industry and change how fiber amplifiers are employed, and possibly prove this concept’s use as a coil resonator or using the coil as a means to convert pump signal into a LASER. Of course, these are hypotheticals assuming the successful development of the device, but very possible ones given the guarantee of future research.

REFERENCES

[1] Quimby, R. (2006). Photonics and Lasers: An Introduction. Hoboken, New Jersey: John Wiley & Sons, Inc.

[2] Bravo, Tyler and Steven Laxton. "Fiber Coil Resonator for Optical Gain" Undergraduate joint thesis. Texas A&M University, 2015. Print.